



## Exergy Analysis of a CO<sub>2</sub> Recovery Plant for a Brewery

Nielsen, Daniel Rønne; Elmegaard, Brian; Bang-Møller, Christian

*Published in:*  
Proceedings of ECOS 2012

*Publication date:*  
2012

*Document Version*  
Early version, also known as pre-print

[Link back to DTU Orbit](#)

*Citation (APA):*  
Nielsen, D. R., Elmegaard, B., & Bang-Møller, C. (2012). Exergy Analysis of a CO<sub>2</sub> Recovery Plant for a Brewery. In U. Desideri, G. Manfrida, & E. Sciubba (Eds.), *Proceedings of ECOS 2012*  
<http://www.ecos2012.unipg.it/public/proceedings/html/E2LA.html>

---

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# Exergy Analysis of a CO<sub>2</sub> Recovery Plant for a Brewery

**D. R. Nielsen<sup>a</sup>, B. Elmegaard<sup>b</sup>, C. Bang-Møller<sup>c</sup>**

<sup>a</sup> Technical University of Denmark, Kgs. Lyngby, Denmark, drni@alectia.com

<sup>b</sup> Technical University of Denmark, Kgs. Lyngby, Denmark, be@mek.dtu.dk

<sup>c</sup> Technical University of Denmark, Kgs. Lyngby, Denmark, cbm@mek.dtu.dk

## Abstract:

A large number of new and old breweries around the world experience increasing energy cost associated with the production of beer. Large heating and cooling demands in the brewing process and a wide use of utilities for assisting the processes necessitate a detailed analysis of individual efficiencies for processes and the different utility plants.

One considerable utility plant is the CO<sub>2</sub> recovery plant, which purifies/purges the CO<sub>2</sub> generated in the fermentation process in order to reuse it in the brewery site or sell it to customers who demand high quality CO<sub>2</sub>.

In the paper a detailed model of a 2000kg/h CO<sub>2</sub> recovery plant for a brewery is presented, which is a typical plant capacity for a large CO<sub>2</sub> self-sufficient brewery. The model includes all significant unit operation in the CO<sub>2</sub> plant and a complete mass and energy balance of it.

In order to prevent hidden loads and misleading analysis; the system is modeled as a final supplier solution, which is initially considered without heat and recovery integration even though this is commonly used.

The following steps are presented. First step introduces the process and the component appearance followed by the energy requirements and corresponding loads. Consumptions and loads are compared with an existing plant at a corresponding capacity and are validated.

Energy and exergy analysis are used in order to illustrate the performance of each individual system component of the CO<sub>2</sub> recovery plant.

A schematic overview of all exergy flows including destruction is presented and proves a clear understanding of the exergy inefficiencies associated with the plant.

The highly detailed and validated model enables and prepares different holistic methodologies and analyses to be used, including thermoeconomic diagnosis and optimization of plant set points.

## Keywords:

Exergy analysis, Grassmann diagram, CO<sub>2</sub> recovery plant, utility plant.

## 1. Introduction

Many breweries all over the world contain a CO<sub>2</sub> recovery system in order to collect the generated CO<sub>2</sub> from the fermentation process and exploit it for the process use. Energy requirements have been investigated in several breweries in order to determine overall electric and thermal demands, e.g. using pinch analysis in order to design the optimal heat exchanger network [1]. Even manual power, such as physical human work has been converted into exergy and included in the analyses [2]. Further evaluations have presented data for exergetic inefficiencies in the various parts of the production lines and comparison with other production sites [1].

### 1.1 Process description

This study examines a CO<sub>2</sub> recovery plant in the application of a brewery. The plant capacity is 2000 kg CO<sub>2</sub> per hour, designed for a typical brewery in the size of 4 million hectoliter of beer per year.

The recovery process is composed of three parts: (1) compression and purification processes, (2) stripping and condensing process finally followed by (3) a pressure storage and evaporation of the CO<sub>2</sub> for use in the production. A cooling facility is assisting the CO<sub>2</sub> plant.

### 1.1.1 Compression and purification processes

A schematic diagram is shown in Figure 1. CO<sub>2</sub> is produced during fermentation of the beer and with a small overpressure it reaches the recovery plant first arriving in the foam trap which discards possible visible gas impurities such as foam generated during fermentation. Water soluble impurities (mainly alcohol) are removed in the water scrubber and the CO<sub>2</sub> is lead to the balloon as a buffer supplying the following two-step-compressors containing inter- and after cooler and dehumidifier. Here the CO<sub>2</sub> has reached a relatively high pressure close to 20bar. After the compression odours are removed in the carbon filters followed by drying the CO<sub>2</sub> to a dew point of -60C in the dehydrator. The carbon filters and dehydrators are regenerated by an electric heating element and by CO<sub>2</sub> purge gas or air.

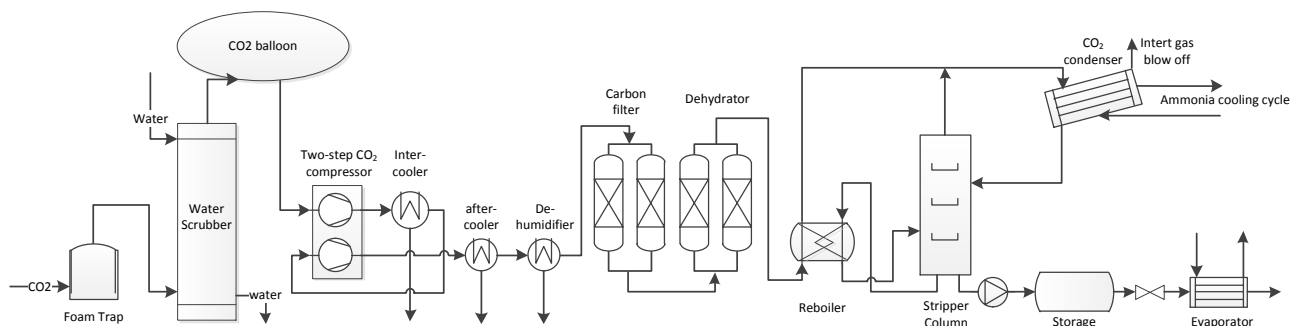


Figure 1: CO<sub>2</sub> compression and purification processes followed by stripping and liquefaction.

### 1.1.2 Stripping and liquefaction process

Purified CO<sub>2</sub> enters the reboiler for the stripping column in which it is pre-cooled before liquefaction in the CO<sub>2</sub> condenser at temperature down to -25°C. Here the CO<sub>2</sub> is condensed to the reflux tank and inert gas is separated and discharged to the surroundings.

Liquid CO<sub>2</sub> is pumped to the top of the stripping column, where further reduction of oxygen and inert gas is obtained. From the bottom of the column liquid CO<sub>2</sub> is partly pumped to the storage tank and partly circulated through the reboiler which heats the column and hereby ensure continuous evaporation. For the simplest plant setup the CO<sub>2</sub> is finally led through a steam heated evaporator before entering the production site, which means that the cooling potential is not utilized due to time constraints.

### 1.1.3 Low temperature cooling facility

Figure 2 shows how the cooling demand is supplied to the CO<sub>2</sub> plant. An ammonia cycle supplies the CO<sub>2</sub> condenser and dehumidifier with cooling at two different stages, which are separated in an economizer. Heat removal from the ammonia condenser is done by a water cycle assisted with a cooling tower that furthermore supplies the inter cooler and after cooler with cooling.

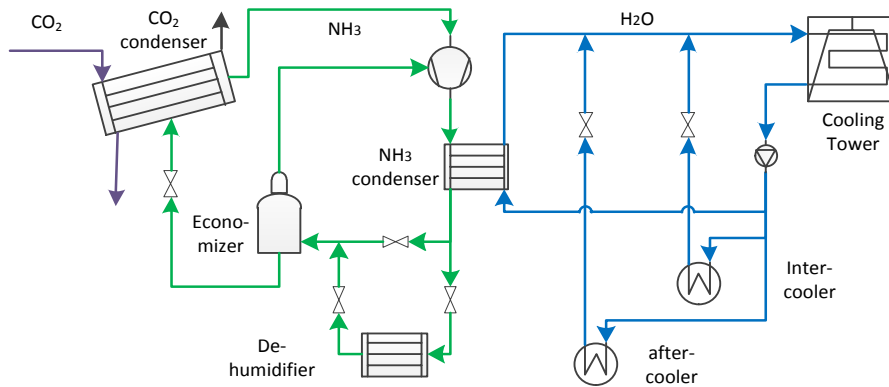


Figure 2: Cooling facility for the CO<sub>2</sub> liquefaction.

#### CO<sub>2</sub> process:

| After component:                  | p [bar] | T [C] |
|-----------------------------------|---------|-------|
| Balloon                           | 1,028   | 34,2  |
| CO <sub>2</sub> compressor step 1 | 4,7     | 192   |
| Inter cooler                      | 4,5     | 40    |
| CO <sub>2</sub> compressor step 2 | 18,4    | 186   |
| after cooler                      | 18,2    | 35    |
| Dehumidifier                      | 18      | 20    |
| Dehydrator                        | 17,6    | 19,5  |
| Reboiler                          | 17,6    | -15   |
| CO <sub>2</sub> condenser         | 17,6    | -23,6 |
| Stripper column                   | 17,6    | -23,6 |
| Storage pump                      | 18,5    | 23,6  |
| CO <sub>2</sub> expansion         | 5       | -56,5 |
| CO <sub>2</sub> evaporator        | 5       | 2     |

#### NH<sub>3</sub> cycle:

| After component:           | p [bar] | T [C] |
|----------------------------|---------|-------|
| Economizer                 | 3       | -12   |
| CO <sub>2</sub> condenser  | 0,95    | -34,6 |
| NH <sub>3</sub> compressor | 14      | 227   |
| NH <sub>3</sub> condenser  | 13      | 35    |
| Dehumidifier               | 4       | 0,7   |

#### Water cycle:

| After component:              | p [bar] | T [C] |
|-------------------------------|---------|-------|
| Pump                          | 3       | 30    |
| NH <sub>3</sub> condenser     | 3       | 33    |
| Inter cooler                  | 3       | 40    |
| After cooler                  | 3       | 40    |
| Mixing (before cooling tower) | 3       | 34,1  |

Tabel 1: Operation states for the CO<sub>2</sub> recovery plant.

## 2. Methodology

An exergy analysis has been performed on a CO<sub>2</sub> recovery plant. The process setup is shown in Figure 1, while states throughout the process is shown in Tabel 1.

#### Assumptions

The following studies have been done on basis of the following assumptions:

- The system operates steady state at maximum capacity.
- Electricity consumed due to regeneration of filters is included due to a time average approach.
- Component efficiencies and heat transfer coefficients do not vary with pressure, temperature or mass flow.
- Only pressure drops in heat exchangers and filters are taken into account, while remaining pressure drops and thermal losses are neglected. E.g. heat transfer to the storage tank is neglected. This loss will cause an extra load in the CO<sub>2</sub> condenser, due to the fact that CO<sub>2</sub> gas is rejected from the tank to the condenser supply line.
- All compressors are cooled by cooling water from the same stream as for the following coolers (inter cooler, after cooler, NH<sub>3</sub> condenser).
- The stripping column is regenerative. It is therefore assumed that the stream out of the reboiler is pure gas and corresponds (due to mass and state) to the evaporation from the stripping column.

- It is estimated that the incoming CO<sub>2</sub> contains 4.2% gaseous water. Chemical exergy in the CO<sub>2</sub> is neglected due to the fact that its impact is less than 0.1%.

#### *Data validation and solution procedure*

Simulations have been made in DNA [3] (Dynamic Network Analysis) which is an open source simulation software [4]. It contains a list of standard components that in this case fulfills the modeling requirements.

Operating parameters, such as compressor isentropic and mechanical efficiencies, pressure drop in heat exchangers, operating states (temperatures and pressures) is all data from a specific plant setup. The simulation has been split into three parts. First part presents CO<sub>2</sub> containing water as a real gas in order to model the compression and condensing of water in the gaseous CO<sub>2</sub>. Second part is a model for CO<sub>2</sub> as cooling media (R744) and it handles the condensing-, stripping- and evaporation process. Finally the cooling facility is modeled as an ammonia refrigeration cycle connected with a water cycle.

The stripping column is regenerative (not external heated), and therefore calculations are based on input and output data which is verified.

#### *Exergy analysis and entropy generation*

Exergy has the advantage that it valorizes energy as potential work and not only consider the mounts of energy available. An exergy analysis of the system will reveal component irreversibilities, which is an expression of entropy generation. This encourages determination of lost available work (or exergy destruction) for each component in the system and mapping of the disappearance of the work added to the system. This analysis provides a reasonable basis for optimizing the system design trough for example a thermoeconomic analysis [5].

For a system or a component only a given amount of work can be transferred to the output stream [6]. This originates in the entropy generation, of which the transferred work is given (1):

$$\dot{W} = \dot{W}_{rev} - T_0 \dot{S}_{gen} \quad (1)$$

which leads to the relation of lost work (2) (the Guoy-Stodola Theorem) [6]:

$$\dot{W}_{lost} = T_0 \dot{S}_{gen} \quad (2)$$

Entropy generation may in some cases appear a bit abstract in order to understand and present lost work. The following representation of exergy is therefore used during the execution of an exergy analysis.

#### *Methodology for exergy analysis*

All exergy transfers in inlets and outlets,  $E_i$  and  $E_e$  are calculated in the model. The exergy of the given stream refer to the maximum theoretical work that can be obtained by bringing the stream to the dead state or environmental state ( $T_0, p_0$ ). Exergy flow is determined on basis of the unit-of-mass exergy [kJ/kg], so called specific exergy (3) [5]. In the case we decide to neglect chemical exergy, because of its neglectable impact, this only represents the phisycal exergy.

$$e^{ph} = (h - h_0) - T_0(s - s_0) \quad (3)$$

Destruction of exergy is calculated by the exergy balance (4):

$$\dot{E}_i = \dot{E}_e + \dot{E}_L + \dot{E}_D \quad (4)$$

In which  $E_L$  and  $E_D$  describes the loss and destruction respectively. For the major part of the components in the respective model, lost streams are not utilized and therefore included as a part of the destruction according to the system.

Destruction will be considered for each component and can be expressed in different ratios. One useful ratio is of the total destruction in the plant (5):

$$y_D^* = \frac{\dot{E}_D}{\dot{E}_{D,tot}} \quad (5)$$

Another representation of the destruction, which is used in this paper, is destruction as a ratio of total fuel input (6):

$$y_D = \frac{\dot{E}_D}{\dot{E}_{F,tot}} \quad (6)$$

This is in order to have the same reference when comparing with exergy streams relatively. For example exergy losses are likewise determined as a rate of the total fuel input (7).

$$y_L = \frac{\dot{E}_L}{\dot{E}_{F,tot}} \quad (7)$$

The final product leaves the plant as requested in the production site. The exergy content of the product stream leads to determine the overall exergy efficiency for the plant (8).

$$\eta_{II} = \frac{\dot{E}_{product}}{\dot{E}_{F,tot}} \quad (8)$$

In cases where the exergy of the final product is equal to the ambient, it may be more evident to focus on the destruction in each component in order to reduce the overall efficiency.

#### *Grassmann diagram for CO<sub>2</sub> recovery plant*

A Grassmann diagram shows a graphical representation of the exergy development throughout the process. The so called exergy diagram illustrates all exergetic inputs and outputs for the entire plant – both the CO<sub>2</sub> recovery process and cooling facility.

Exergy inputs and outputs related to the product streams, power inputs, waste streams and exergy interactions due to heat exchangers determines the destructions. All these are shown for each incorporated component in the diagram.

This exergy flow representation provides a valuable overview of the plant details which energy considerations alone cannot accommodate. It locates/pinpoint destruction of exergy and may provide better knowledge in order to improve the overall performance in a CO<sub>2</sub> recovery plant [7]. A Grassmann diagram of the investigated CO<sub>2</sub> recovery plant is shown in Figure 7.

### **3. Results**

#### *Energy demand for the isolated CO<sub>2</sub> recovery process*

Figure 1 shows the energy demands for the isolated CO<sub>2</sub> recovery process, i.e. without the cooling facility. It appears that the total energy consumption is 767kW, contributed by cooling, heating and electricity with a share of 51.6%, 24.6% and 23.8% respectively.

The majority of electricity is consumed in the CO<sub>2</sub> compressors, while a minor part is consumed due to pumps and regeneration of filters.

A little more than half of the consumption is related to a cooling demand. Apparent is the cooling needed for CO<sub>2</sub> condensing, which contributes with 25% of the total consumption. A similar amount of cooling demand is needed in order to remove the heat generated due to the compression stages. Out of these 205kW it appears that 15% are expended on condensing water due to humidity.

After the recovery process the CO<sub>2</sub> is delivered to the production as gas at a reduced pressure. This expansion generates a cooling effect that has to be removed corresponding to another 25% of the total energy demand.

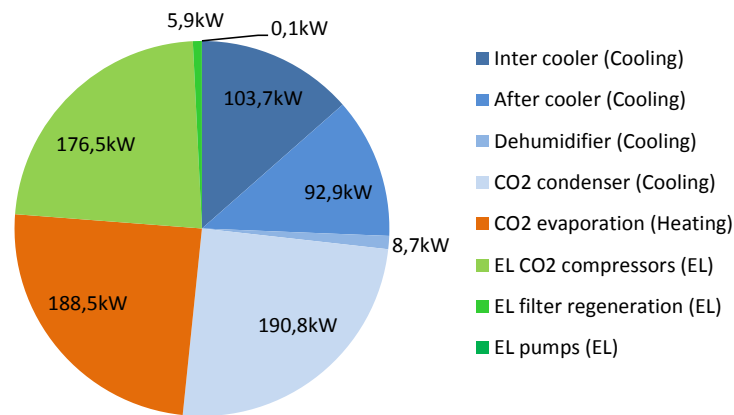


Figure 3: Energy demands for the isolated CO<sub>2</sub> recovery process.

#### Exergy expenditure in the isolated CO<sub>2</sub> recovery process

Converting the previous energy demand analysis into an exergy consideration of input and output exergy streams (cf. Figure 4), the following is observed:

- Total exergy input/output is 220kW.
- Electricity consumption remain unchanged, thus its share of the total consumption increases.
- The large cooling consumption for the CO<sub>2</sub> condenser (190.8kW) is strongly reduced to 20% (37.3kW) due to the exergy perspective.
- Cooling in the inter cooler, after cooler and dehumidifier are all above ambient temperature, which in the exergy perspective has been added to the output as a hot waste stream. Accordingly the energy flow (205kW) reduces to 9.6% (19.7kW) exergy.
- Evaporation of CO<sub>2</sub> is added as an output stream because of its cooling potential. This stream is also reduced (from 188.5kW energy) to 36% (67.3kW) when based on exergy.
- The CO<sub>2</sub> product appears to leave the plant containing 23.1% of the total exergy.
- Finally the exergy destruction occurs due to lost streams and other thermal irreversibilities. This share represent 58.9kW corresponding to 26.7% of the total output exergy.

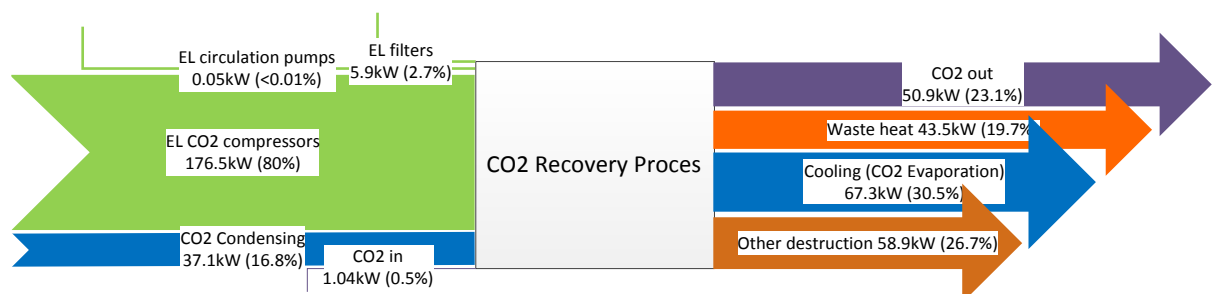


Figure 4: Exergy expenditure in the isolated CO<sub>2</sub> recovery process.

### Energy demand for the entire CO<sub>2</sub> recovery plant

Considering the demand in the existing CO<sub>2</sub> recovery plant setup (Figure 5) the supply of cooling facility increases the consumption by 30% which results in a total energy consumption of 991kW. The heating demand remains constant while the electricity consumption is extended by an ammonia compressor of 110kW. The cooling demand keeps its share of 51%. All 507kW cooling of the plant is placed in a cooling tower.

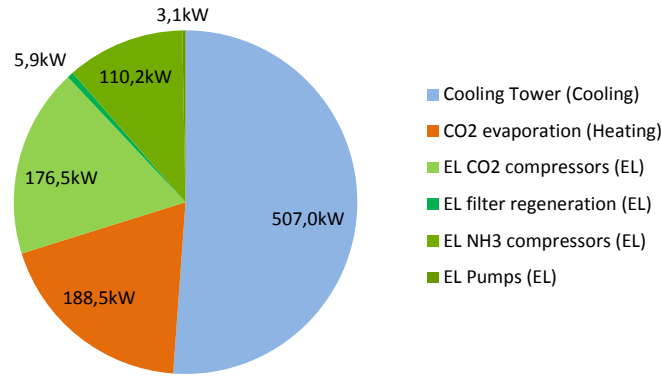


Figure 5: Energy demands for the entire CO<sub>2</sub> recovery plant.

### Exergy expenditure for the entire CO<sub>2</sub> recovery plant

Figure 6 shows the input and output exergy streams for the entire plant and the following can be observed:

- Total exergy input/output is 358kW.
- Electricity still remains unchanged, but as a major part, 83% of the exergy input, while the heating demand (of 188.5kW) is replaced by steam consumption reduced to 32% (61.2kW) exergy
- The exergy output of CO<sub>2</sub> remains unchanged and has a share of 14.2%.
- Cooling demand of 507kW is all rejected in the cooling tower as heat just above the ambient temperature, which reduces to 2.2% (7.7kW) exergy of waste heat and becomes a part of the exergy destruction.
- Due to the steam input a small amount of 2% exergy is leaving as return condensate.
- As much as 82.6% of the exergy output disappears as thermal irreversibilities and streams that are being discharged to the environments.

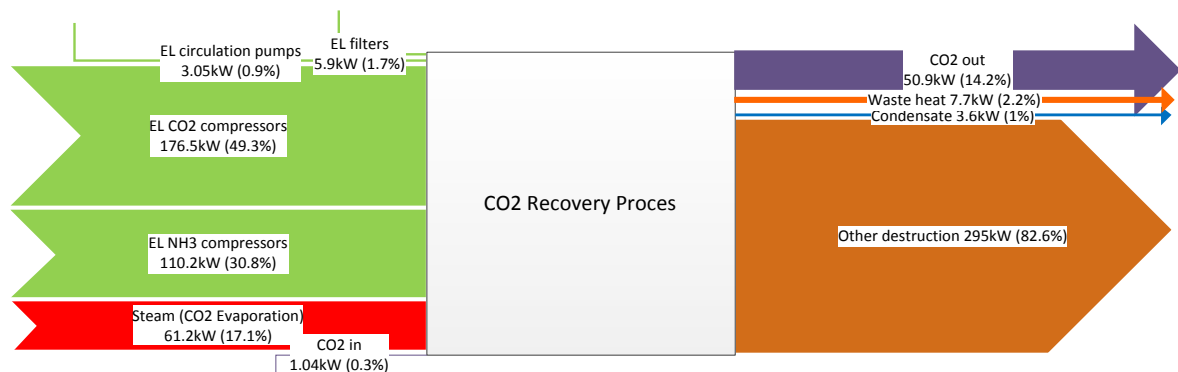


Figure 6: Exergy expenditure in the entire CO<sub>2</sub> recovery plant.



The consumption of the pressurized CO<sub>2</sub> in the production site and return of condensate to a given boiler results in an overall exergy efficiency for the CO<sub>2</sub> recovery plant of 0.15. However utilization of the cooling potential due to the CO<sub>2</sub> evaporation would increase the exergy efficiency to 0.5.

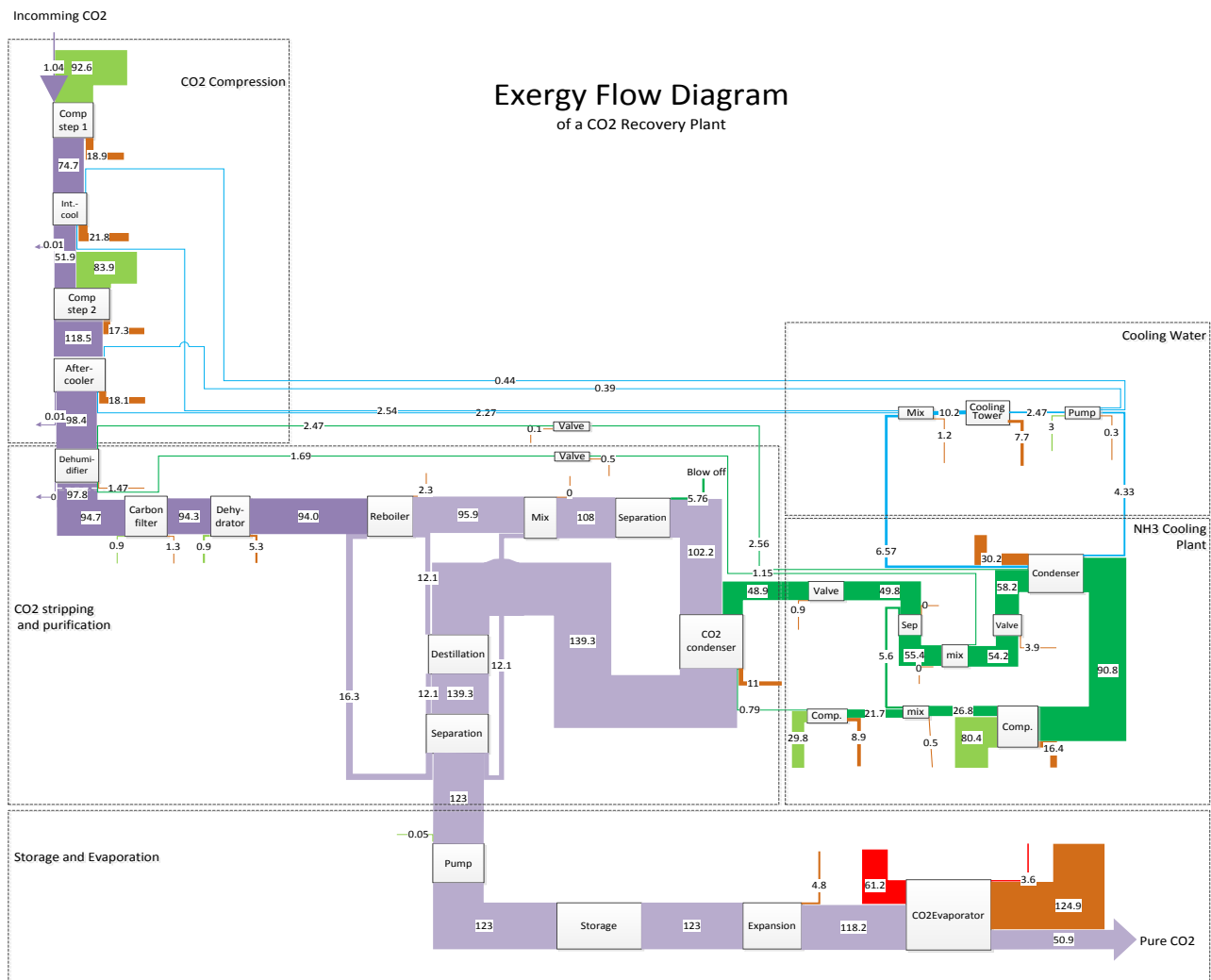


Figure 7: Grassmann diagram of the exergy flows in a CO<sub>2</sub> recovery plant complemented by cooling facilities.

#### Exergy appearance in CO<sub>2</sub> recovery plant in details

Figure 7 shows the exergy formation throughout the recovery plant and Figure 8 describes the exergy destruction in each single component as a ratio of the total fuel input. The following observations are made:

#### CO<sub>2</sub> process

- As long as the cooling potential due to CO<sub>2</sub> evaporation and the waste heat streams are not utilized, the total exergy destruction associated with the recovery plant becomes 85% (303kW), of the total fuel exergy input of 357kW.
- 35% of the input exergy is destroyed due to the CO<sub>2</sub> evaporation, which is a result of using steam containing a high exergy value in order to heat the low temperature CO<sub>2</sub> that also has high exergy content as cooling potential.
- Due to the compressor inefficiencies 10.1% of the total exergy input is destroyed.

- Waste heat after the two compression steps is generated, even though 11.2% of the exergy input is disposed by cooling water. The following dehumidifier causes another 0.4% of destruction.
- Temperature difference between NH<sub>3</sub> and CO<sub>2</sub> in the CO<sub>2</sub> condenser carries 3% destruction of the input exergy.
- Minor exergy destruction is the CO<sub>2</sub> expansion of 1.4%. Regeneration of carbon filter and dehydrator entails 1.9% and the reboiler 0.6%. Finally to be mentioned is the blow off loss stream that carry another 1.6% of the input exergy.

#### Cooling facility

- Inefficiencies in NH<sub>3</sub> compressor induces 7% destruction, while the heat generated and disposed in the NH<sub>3</sub> condenser carries 8.4% of the total exergy input.
- Only 2.1% is destroyed in the cooling tower in spite of the relatively large heat disposal (Figure 5). The exergy destruction connected to this large amount of energy is placed in the local heat exchange such as NH<sub>3</sub> condenser, inter cooler and after coolers.
- Finally some minor destructions are found due to expansion valves, pump inefficiencies and mixing of medias containing different temperature levels.

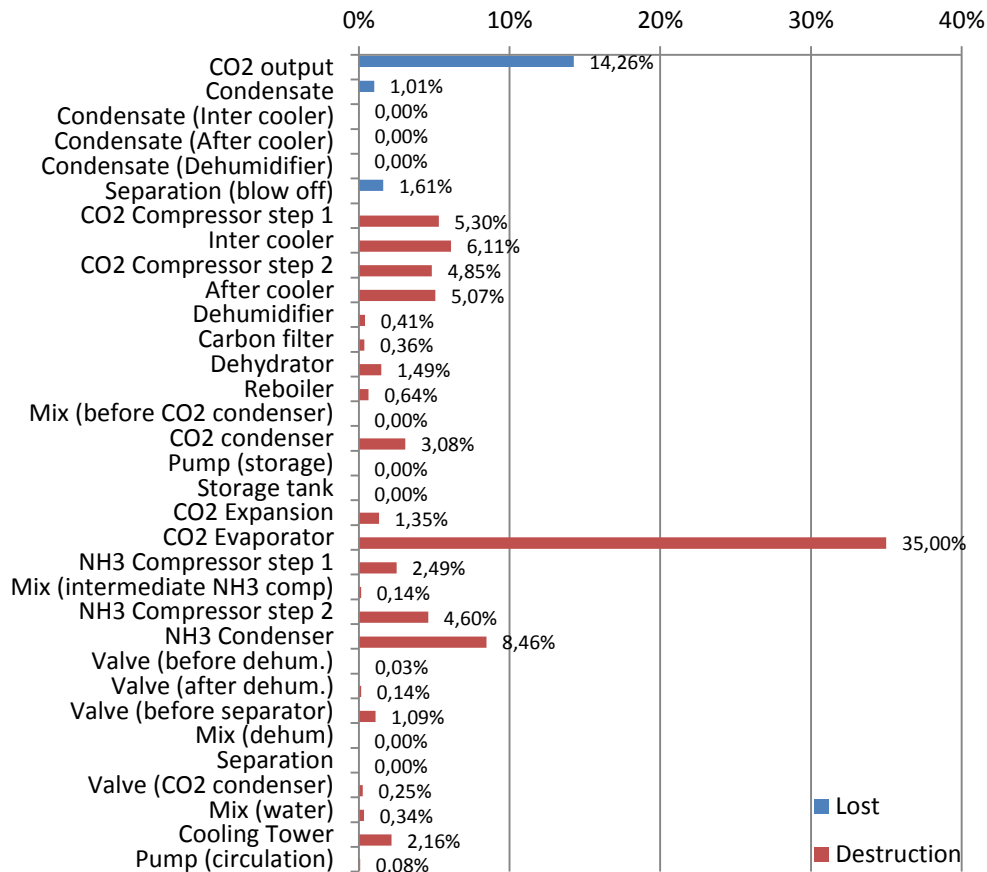


Figure 8: Exergy destruction in each component as a ratio of the total fuel input.

Evaluation of the cooling plant shows that the ammonia refrigeration cycle contributes with 200kW cooling of energy, in which 191kW and 9kW is located in the CO<sub>2</sub> condenser and dehumidifier respectively.

The total electricity input is 110kW which gives a COP of 1.81. Reconfiguration of temperatures may lead to less exergy destruction and therefore higher energy efficiency. By increasing the evaporation temperature both COP will increase and less exergy destruction in the evaporator (CO<sub>2</sub> condenser) is obtained.

The total cooling load of the entire cooling system (including the water cycle) is 396kW of energy which lead to a COP of 3.5. What is relevant to notice is the introduction of circulation of water, which transports and disposes heat from above ambient temperature to the ambient trough a cooling tower.

In order to reduce the exergy destruction the operating temperatures in the NH<sub>3</sub> cycle may be analyzed.

#### **4. Discussion**

The major sinner of the plant turns out to be the CO<sub>2</sub> evaporator that destroys 35% of the total exergy input. CO<sub>2</sub> should obviously not be evaporated by steam (according to an energy/exergy perspective). Apparently, the cooling potential associated with the CO<sub>2</sub> expansion has to be utilized. In order to exploit most of the refrigeration potential as possible, it is necessary to locate low temperature cooling demands. Since the condensing of the CO<sub>2</sub> involves the lowest temperature demands in the brewery the evaporation may be utilized in order to cool the CO<sub>2</sub> condenser – directly or indirectly. Due to time constraints between production and consumption of CO<sub>2</sub>, it may be necessary to introduce thermal heat storage (sensible or latent).

Almost 10% of the total exergy input is destroyed due to thermal degradation in the ammonia condenser. A reduction of the condensing temperature or an exploitation of this excess heat may therefore be important in order to obtain a reduction in the total energy consumption of a brewery. Moreover, excess heat corresponding to 11.1% of the exergy input is destroyed in inter- and after cooler, of which 15% is due to condensing of water. A reduction of the water content in the incoming CO<sub>2</sub> will accordingly contribute in the reduction of cooling demand.

Compressor inefficiencies represent 17.1% destruction of the total exergy input, which encourage investigating the technical and economic feasibility in using more efficient compressors.

The analysis performed enables a thermoeconomic analysis on the system design and further evaluation of optimal operating set points.

#### **5. Conclusion**

An analysis of energy demands for the CO<sub>2</sub> recovery process has been made, which gives a good foundation for determining capacities/plant dimensions for cooling facilities, heat- and power supply. The analysis has been extended by an exergy analysis in which it turns out to be more representable to illustrate some demands, such as the waste heat and cooling potential (CO<sub>2</sub> expansion) as output streams rather than input streams. This enables a more detailed analysis of the energy consumption and utilization through the plant.

The same has been concluded in a corresponding analysis for the entire plant setup.

An exergy analysis has been performed on a complete CO<sub>2</sub> recovery plant setup and presented in a Grassmann diagram in which amounts of input and output exergies are shown graphically. This presentation improves the understanding of the exergy (or value of energy) appearance in the process.

A schematic overview of all exergy output including destructions has been presented as a ratio of the total exergy input. This provides a clear understanding of the exergy inefficiencies associated with the plant – in other words a description of where the valuable energy disappear in the system.

The major contributors to the exergy destruction constitutes of the CO<sub>2</sub> evaporation (35% of the total exergy input), followed by the temperature degradation of generated heat due to compression of CO<sub>2</sub> and NH<sub>3</sub> and destruction associated with compression irreversibilities.

## Acknowledgement

Union Engineering is acknowledged for sharing data for plant setup and operational states.

## Nomenclature

|                     |   |
|---------------------|---|
| $e^{ph}$            | physical specific exergy                          |
| $\dot{E}_D$         | Exergy destruction                                |
| $\dot{E}_{D,tot}$   | Total exergy destruction                          |
| $\dot{E}_e$         | Exergy output                                     |
| $\dot{E}_{F,tot}$   | Total fuel exergy input                           |
| $\dot{E}_i$         | Exergy input                                      |
| $\dot{E}_L$         | Exergy loss                                       |
| $\dot{E}_{product}$ | Exergy in product                                 |
| $\dot{S}_{gen}$     | Entropy generation                                |
| $\dot{W}$           | Work  |
| $\dot{W}_{rev}$     | Reversible work                                   |
| $\dot{W}_{lost}$    | Lost work   |
| $\gamma_D$          | Destruction ratio of the total input              |
| $\gamma_D^*$        | Destruction ratio of the total exergy destruction |
| $\gamma_L$          | Exergy loss as ratio of the total exergy input    |
| $\eta_{II}$         | Second law efficiency                             |

## References

- [1] Muster-Slawitsch B, Brunner C, De Lima DR, Schnitzer H, Muster-Slawitsch B, Brunner C. The Green Brewery concept - Energy efficiency and the use of renewable energy sources in breweries. Chem Eng Trans 2010;21:649-54.
- [2] Fadare DA, Nkpubre DO, Oni AO, Falana A, Waheed MA, Bamiro OA. Energy and exergy analyses of malt drink production in Nigeria. Energy 2010;35:5336-46.
- [3] B. Elmegaard NH. DNA - A Thermal Energy System Simulator <http://orbit.dtu.dk/RecordLinkPage.external?sp=recid&sp=231251>. 2009.
- [4] Elmegaard B, Houbak N. Software for the Simulation of Power Plant Processes. Proceedings of ECOS 2002 2002.
- [5] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: Wiley-Interscience, 1996.
- [6] Bejan A. Advanced engineering thermodynamics. Hoboken,N.J.: Wiley, 2006.
- [7] Thomas RJ, Ghosh P, Chowdhury K. Application of exergy analysis in designing helium liquefiers. Energy 2012;37:207-19.